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ARC HEATER DEVELOPMENT AT AEDC*

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Abstract

The USAF/Arnold Engineering Development Center (AEDC) has undertaken an arc heater development program to develop a large, high-pressure, high-power arc heater capability. A large, state-of-the-art segmented arc heater (H3) is presently under development and is scheduled to be fully operational at chamber pressures up to 115 atm with a total power of 60 MW by late 1995. The H3 arc heater is a 50-percent geometric scale-up of the existing H1 segmented arc heater and is designed to operate at 2.25 times the power of H1. Future plans also include high-pressure (250 atm) segmented arc heater development, and development of a larger, higher power capability by manifolding several arc heaters into a single plenum or by developing a single very large arc heater. AEDC has also developed an extensive analytical capability to assist in the design and development of segmented arc heaters. This paper describes the present arc heater testing capabilities and development activities, along with future arc heater development plans.

Introduction

Hypersonic testing requirements for propulsion, materials, and structures dictate high pressures and temperatures not attainable by conventional means. Electric arc heaters are the only viable method of heating air to high temperatures (5,000 - 15,000 °R) for durations of several minutes (Fig. 1) which is necessary for testing airframe structures and scramjet engines above Mach 8. Existing arc heaters are not capable of meeting all of the hypersonic testing requirements. The AEDC development effort is extending the size and performance capabilities of arc heaters to satisfy more of the hypersonic testing needs.

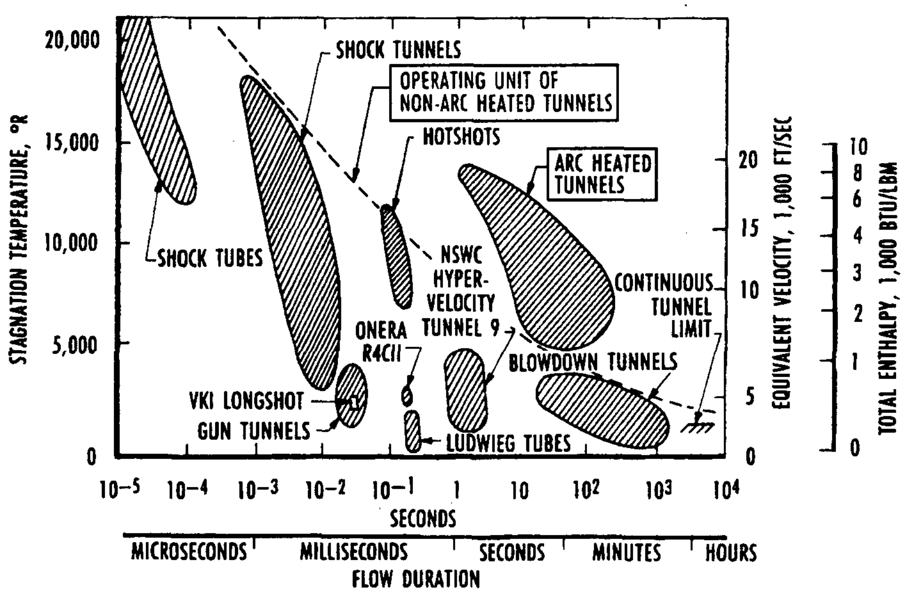

Figure 1. High temperature tunnel capabilities.

Background

Electric arc heaters have been used for aeronautical test purposes since the late 1950's, with the advent of long-range ballistic missiles and the associated need for testing of thermal protective materials for reentry bodies. AEDC has developed and operated arc heaters since 1962. The nation's premier high-pressure arc-heated facility (H1) was developed at AEDC beginning in 1976[1] and has been the workhorse facility for the past 14 years. The 50-MW Reentry Nosetip (RENT) Facility heater was relocated from Wright-Patterson Air Force Base

*The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command (AFMC). Work and analysis for this research were done by personnel of Calspan Corporation/AEDC Operations, technical services contractor for the AEDC aerospace flight dynamics facilities. Further reproduction is authorized to satisfy needs of the U. S. Government.

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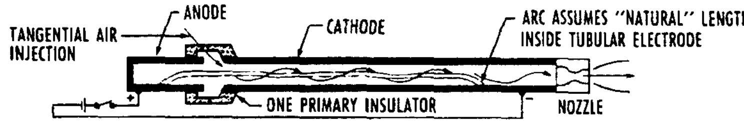
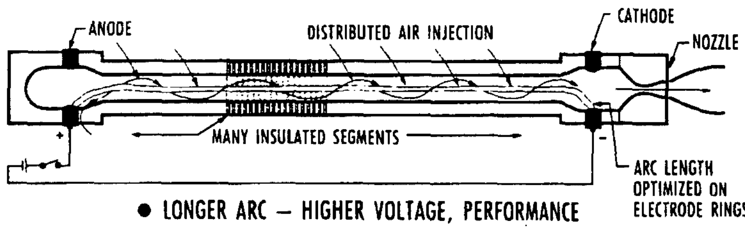
(WPAFB) to AEDC in 1981 and is now the HR facility. The 50-MW High Temperature Leg (HTL) Facility was relocated from WPAFB to AEDC in 1986 and is now the H2 facility. Both the HR and H2 facilities use Huels-type heaters. AEDC has continued to improve the H1 heater over the years through technology test entries. Technology entries have demonstrated operation of the H1 heater at a chamber pressure up to 150 atm and have included various arc heater diagnostic experiments. Results from several of the arc heater diagnostic experiments are presented in Ref. 2. An aggressive analytical effort has been ongoing for several years to address such technical issues as arc stability and reliability, electrode erosion, flow quality, scaling parameters, throat cooling, wall heat flux, and pressure containment. AEDC is presently developing the next generation arc heater (H3), which is a 50-percent geometric scale-up of the H1 heater, designed to operate at a power of 60 MW and mass flow of 15 lbm/sec, 2.25 times the values in H1.



- TUBULAR ELECTRODES – SIMPLE, DURABLE
- PERFORMANCE LIMITED BY NATURAL ARC LENGTH
- EXAMPLE: HEAT/HR, H2 FACILITY

a. Huels type arc heater



- LONGER ARC – HIGHER VOLTAGE, PERFORMANCE
- COLUMN INSULATION REQUIRES SEGMENTATION
- HIGH PERFORMANCE AT COST OF COMPLEXITY
- EXAMPLE: HEAT/H1 FACILITY

b. Segmented type arc heater

Figure 3. Basic arc heater types.

Present Capabilities

The AEDC arc heater facilities (Fig. 2) are located in two adjacent buildings the High Temperature Laboratory (HTL) and the High Temperature Laboratory Addition (HTLA). The HTL houses three production testing arc facilities, while the HTLA has two test stations which are used for arc heater development. The five test units in the two buildings share auxiliary systems, including a high-pressure air supply, high-pressure cooling water systems (demineralized and raw water), a high-speed data acquisition system, and a 60-MW direct-current power supply. The present testing capabilities of the test units located in the HTL are described below.

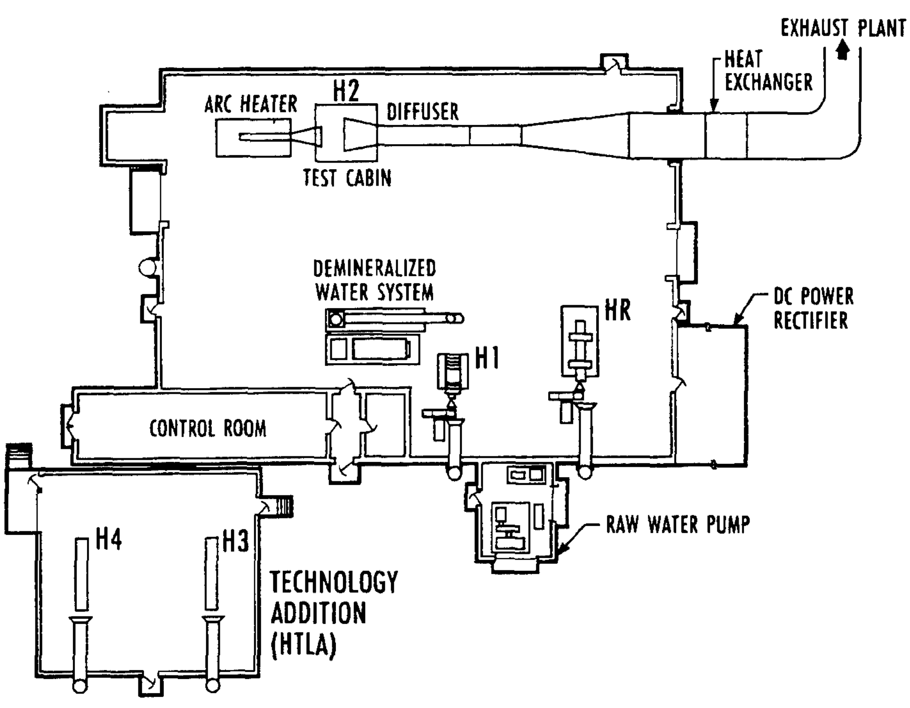


Figure 2. The AEDC high temperature laboratory.

Facilities

The HTL houses three continuous-flow, DC arc-heated facilities: H1, HR, and H2 test units. The HR and H2 test units utilize a conventional Huels-type arc heater consisting of two coaxial tubular electrodes separated by a swirl chamber, as shown in Fig. 3a. The Huels-type heaters are characterized by simplicity, durability, reliability, and operational maturity, but limited performance. The H1 test unit utilizes a segmented arc heater having 200 electrically isolated segments separating the anode (upstream end) and cathode (nozzle end), located at opposite ends of the heater, as shown in Fig. 3b. The segmented arc heater offers not only higher pressure and enthalpy capability, but also

much less contamination from electrode erosion, since it operates at higher voltage and lower current. Typical operating conditions for the H1 heater are approximately 20,000 volts, 1,200 amps at a chamber pressure of 115 atm, which produce a flow-field bulk (mass-averaged) enthalpy of approximately 3,000 Btu/lbm. The HR and H2 Huels-type heaters typically operate at slightly lower chamber pressure (60 to 70 atm) and enthalpy (2,000 to 2,700 Btu/lbm) than the segmented H1 arc heater, but can operate at a higher air mass flow rate (up to 10 lbm/sec).

Each of the HTL test units is equipped with a multiple strut, remotely controlled, rotary model positioning system (MPS). The MPS has an axial drive which can adjust the position of the models in the flow field.

The H1 and HR facilities expand the arc-heated air in a supersonic free jet to atmosphere. Both heaters are equipped with a family of interchangeable nozzles. The largest contoured nozzle in the H1 facility has an exit diameter of 3.00 in. with an exit Mach number of 3.5. The HR test unit has a 4.00-in. exit diameter contoured nozzle with a Mach number 3.16. The HR facility also has a semicircular nozzle with a flat lower surface which can be used to test large, flat material samples. Flared nozzles that are available in the H1 and HR facilities produce a continually expanding flow field and a continuously varying impact pressure with axial distance from the nozzle exit. Dust injection capability is also available in the H1 facility.

The H2 test unit is a relatively new facility at AEDC[3] and is equipped with a test cabin which allows the arc heated flow to be expanded to lower exit static pressures (higher Mach numbers). Interchangeable conical expansion sections provide nozzle exit diameters of 9, 24, and 42 in. with Mach numbers ranging from 4.0 to 8.6.

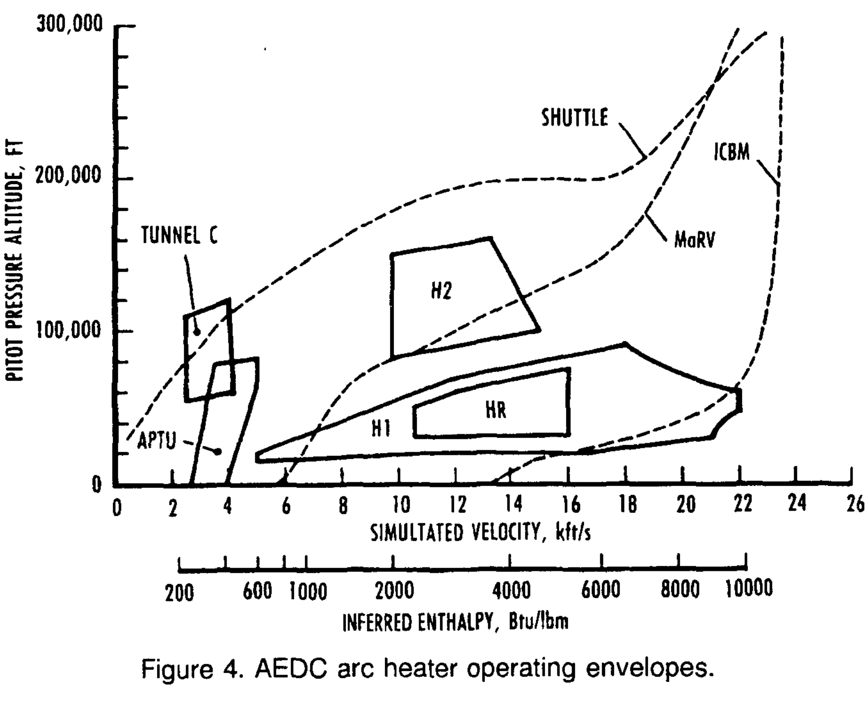


Figure 4. AEDC arc heater operating envelopes.

The maximum test model size is limited by the nozzle exit plume diameter in the H1 and HR facilities. The test models in the H2 facility, although larger, are also limited in size by the nozzle exit diameter and the potential of the model to block the diffuser flow.

The arc facilities produce the high heating, pressure, and shear conditions encountered during reentry and hypersonic flight, so that flight materials can be tested for time periods close to flight heating times. Run time at maximum enthalpy is approximately two minutes for the Huels-type heater and approximately one minute for the segmented heater. The aerothermal performance of the three arc facilities is presented in Fig. 4.

Test Techniques

The various test techniques used in the AEDC arc facilities to simulate certain aspects of hypersonic flight are briefly described in this section with reference to previously published works on the various test techniques.

Nosetip ablation/recession tests are performed in the arc facilities by positioning the nosetip within the expansion wave from the exit of a contoured nozzle. This exposes the nosetip to constant flow-field conditions. The nosetip is maintained at a specified distance from the nozzle exit by moving the MPS forward as the model ablates. A laser beam is propagated normal to the flow centerline to provide a predetermined reference point for the system which controls the model axial location. Tests at angle of attack can also be run with special strut adaptors.

Boundary-layer transition tests are performed using a flared nozzle which creates a continually expanding flow field. The model is injected in the flow at some distance downstream of the nozzle exit where the impact pressure is low, and moved forward in the direction of increasing impact pressure until the nozzle exit is reached. The transition test techni-

que provides data on the shape change history of a reentry vehicle nosetip and allows a determination of the impact pressure at which the flow undergoes transition from a laminar to a turbulent boundary layer.

Reentry vehicle heat-shield material, heat-shield material interfaces, antenna window material, and antenna window transmission performance are tested in the arc facilities using a wedge test technique. The test material is mounted on a wedge of a specific angle to provide the desired heat flux and surface pressure. Different test conditions on the wedge surface can be obtained by locating the test article on or below the centerline of the test rhombus, by using various wedge angles, and by using different Mach number nozzles and heater conditions. The technique for testing the performance of hot antenna windows in the arc facilities is presented in Refs. 4 and 5.

The H1 test unit has the capability of particle injection and acceleration for combined ablation/erosion testing. Dust acceleration extensions are added to the exit of the H1 nozzle to provide a longer transit time for the particles to be drag-accelerated. Both nosetip and wedge models are tested in this configuration.

The capability exists in the H2 test facility to test and evaluate propulsion performance and hardware survivability. Plans were developed and some hardware designed and fabricated to test an operating scramjet combustor in a direct-connect mode; however, funding constraints resulted in cancellation of the project. The planned scramjet test effort in the H2 facility is described in Ref. 6.

A number of diagnostic devices are used in the arc facilities, including high-speed motion pictures, infrared imaging cameras, surface pressure and temperature distribution probes, nosetip profile shadowgraph, pitot pressure probes, and stagnation point heat flux probes. The capability to measure real-time recession on flat surfaces in high-enthalpy flows has been developed and demonstrated at AEDC[7] and is now used as a standard data acquisition technique. A high-speed (5,000 points per sec) data acquisition system is available for fast-response data.

Future Requirements

Hypersonic testing requirements presently exceed national testing capabilities. Larger, higher performance arc heaters are required to meet the testing needs, particularly for hypersonic airframe structures and propulsion systems above Mach 8. A larger flow field is required to accommodate large components such as radomes, sensor windows, and control surfaces of hypersonic glide vehicles. Aerothermal testing also requires long run time and high enthalpy. Higher pressures are required for leading edge, nosetip, and propulsion testing. These improvements in test facility capabilities will only become more critical for future hypersonic testing requirements.

AEDC Development Plan

The approach to developing a larger arc heater capability is to apply the best design concepts available from experience with existing arc facilities, both at AEDC and elsewhere, apply the best analytical design tools available, and develop the next generation arc heater to the maximum capability consistent with design goals and available utilities. The program must be broad enough to include the development of a wide range of analytical capabilities, where deficiencies now exist, in order to understand and predict experimental results. The program must produce arc heaters which meet reliability and performance goals and produce an associated arc heater technology base.

The initial goal of the AEDC arc heater development plan will be the development of a larger arc heater, H3, designed to operate at approximately 2.25 times the power of H1. Next, the plan will focus on increasing the operational pressure of segmented arc heaters and applying this technology to the H3 heater. Future arc heater development programs will rely heavily on the experience with the H3 development effort. An important feature of the AEDC plan is its incorporation of interim improvements in arc heaters into existing aerothermal test facilities. H3 will be used in place of H1 or HR to allow the testing of larger models and material samples. H3 will also be installed in the H2 facility to extend the capability of H2 to higher pressure, enthalpy, and power.

Large Arc Heater Development - H3

AEDC is focusing on the development of the segmented-type arc heater over the Huels-type heater because of the improved performance and flow quality of a segmented heater over the Huels-type heater. The H1 heater was used as the starting point to expand the segmented arc heater technology base. Knowledge gained from experience with the H1 heater and results from analytical modeling efforts have been incorporated into the H3 heater design and will be used during the development of the H3 heater. Specifically, the H1 heater was used to address scale-up issues such as arc stability, operational reliability, air injection configuration, power supply interaction, electrode erosion, flow quality, bore length-to-diameter ratio, throat-to-bore diameter ratio, and scaling relations.

The High Temperature Lab Addition (HTLA), constructed specifically for arc heater development, is located adjacent to the HTL building and utilizes the existing HTL utilities. The HTLA building houses two independent test stations intended for large arc heater and high-pressure arc heater development. The H3 arc heater is presently under development in the HTLA and is scheduled to be fully operational at chamber pressures up to 115 atm by late 1995. The H3 heater is shown in Figs. 5 and 6 prior to the connection of the air and cooling water hoses.

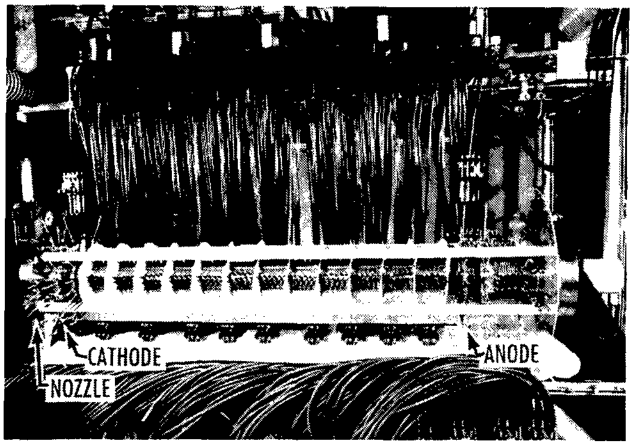


Figure 5. H3 arc heater.

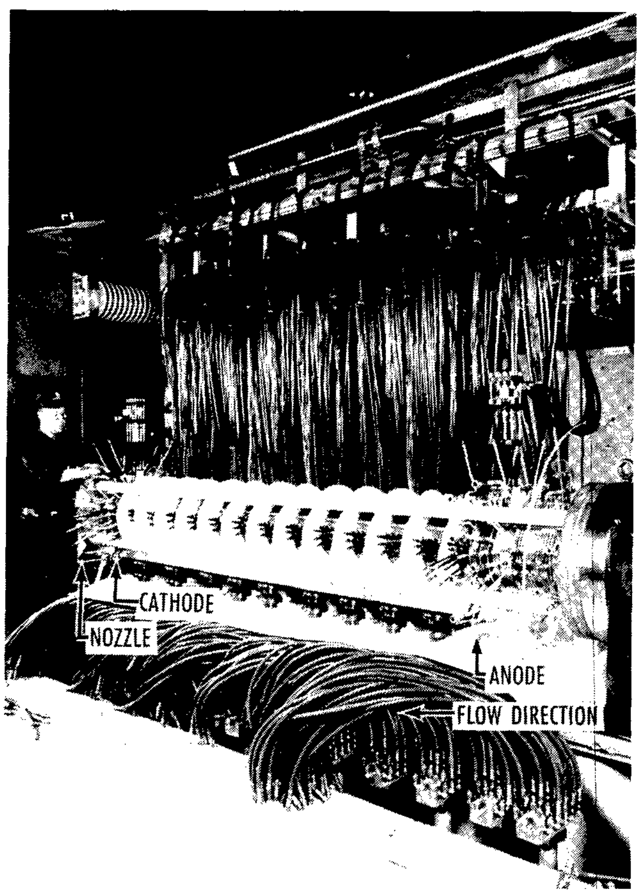


Figure 6. H3 arc heater.

The H3 heater is basically a 50-percent geometric scale-up of the H1 segmented heater and is designed to operate at 80 MW (2.25 times the power of H1); however, the present power supply will limit H3 operation to approximately 60 MW. The H3 heater is designed as a pressure vessel for 200 atm with an operational pressure of 150 atm. The heater has a bore diameter of 3 in. and electrode diameter of 4 1/2 in., with the anode located upstream and the cathode downstream as shown in Fig. 7. Four nozzles have been designed with throat diameters of 0.9, 1.10, 1.35, and 1.65 in. The 1.35-in. nozzle throat diameter corresponds to the 50-percent scale-up of the standard H1 nozzle throat diameter of 0.9 in. In the heater bore, each group of eighteen segments is bound together into a module to simplify assembly and disassembly of the heater. The heater can be assembled using 8, 10, or 12 modules, giving a distance between electrodes of 67.2, 81.6, and 96.0 in. respectively. The 12-module configuration corresponds to the 50-percent geometric scale-up of H1. The total heater length from end flange to nozzle flange is approximately 11 ft.

Air is injected tangentially into the heater at both electrodes and at every segment in the heater bore. A sapphire window is installed in the end cap to permit viewing the anode region and to determine the anode arc rotation rate during operation. Air is also injected over the end cap window to keep the window cool and clean. Air only is injected into the heater. Argon is not used at the electrodes, contrary to the practice in many other arc facilities. A special mixing-air section has been designed and fabricated to be installed downstream of the cathode to provide the capability for injection of cold air to lower the total enthalpy. The cold air mixing section has the capability to inject up to 68 percent of the total air flow.

Four magnetic coils are located in the housing of each electrode to assist the arc attachment positioning and rotation. These coils are connected in series with the electrodes, and an additional power supply for the coils is not required. Initial coil configurations were determined based on experience with H1 and analytical work performed at AEDC.[8] The coil configuration can be quickly and easily changed using connectors external to the heater. The electrode liners are easily removed from the housing for replacement.

The H3 heater is extensively instrumented in a similar fashion to H1. The cooling water flow rate and temperature rise are individually measured for every component or module in the heater: column modules, tapered modules, electrodes, electrode spacer components, nozzle segments, upstream segments,

electrode coils, end cap and nozzle. The total cooling water manifold flow rate and temperature rise for the arc heater are also measured and compared to the sum of the individual measurements. The total heat flux for each component or module is determined from the water flow rate and temperature rise. Twenty-four voltage measurements are made on the wall of the arc heater from the end cap to the cathode. The total voltage and current from the power supply rectifier are also measured. The heater chamber pressure is measured at two locations upstream near the end cap and at one location downstream between the cathode and nozzle. The air mass flow rates are determined using subsonic and choked venturis. The heater air and the mixing air are metered through two separate manifolds allowing separate air mass flow rate measurements using choked venturis.

A number of parameters are measured to constantly evaluate the health of the heater during operation and to quickly terminate the run if any problems are detected. Selected voltages, pressures, flow rates, and temperatures are monitored to ensure the values are within a specified range. If any of the monitored parameters are outside the specified range, the run is terminated. The flow field is monitored by passing a laser beam through the flow perpendicular to the flow axis and measuring the intensity of the laser beam. If a failure is imminent, excessive particles in the flow such as copper or water droplets will cause the detected laser beam intensity to drop. If the laser beam intensity drops below a specified level, the run is terminated. The flow field is also monitored using a copper spectral emission detector. If excessive copper is detected in the flow field, the run is also terminated. The detection sensitivity of the laser and the copper spectral emission detector can be adjusted.

The performance envelopes for H3 have been estimated using empirical scaling relations derived from data of three high-pressure segmented arc heaters. The projected chamber pressure and bulk (mass-averaged) enthalpy envelope with lines of constant current and mass flow rate is shown in Fig. 8 for the 1.35-in.-diam nozzle throat. The corresponding voltage-current envelope with lines of

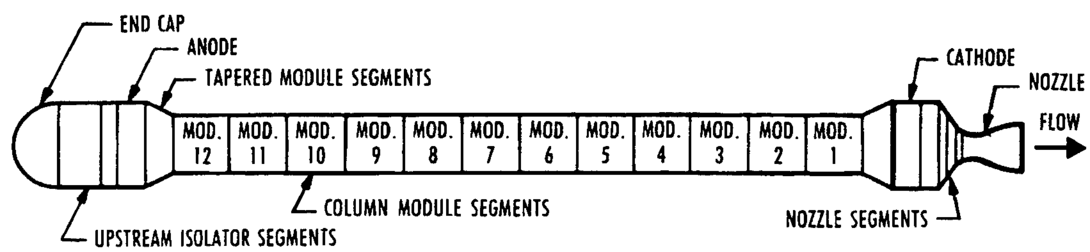


Figure 7. Layout of the H3 arc heater

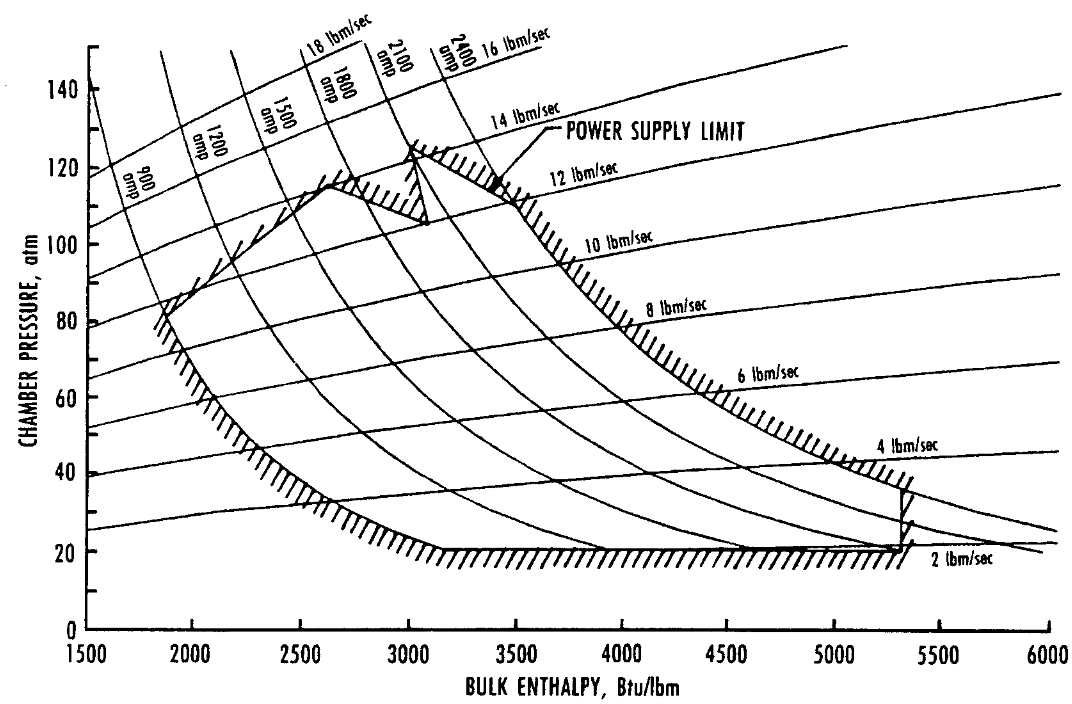


Figure 8. H3 pressure - enthalpy envelope with 1.35-in.-diam throat.

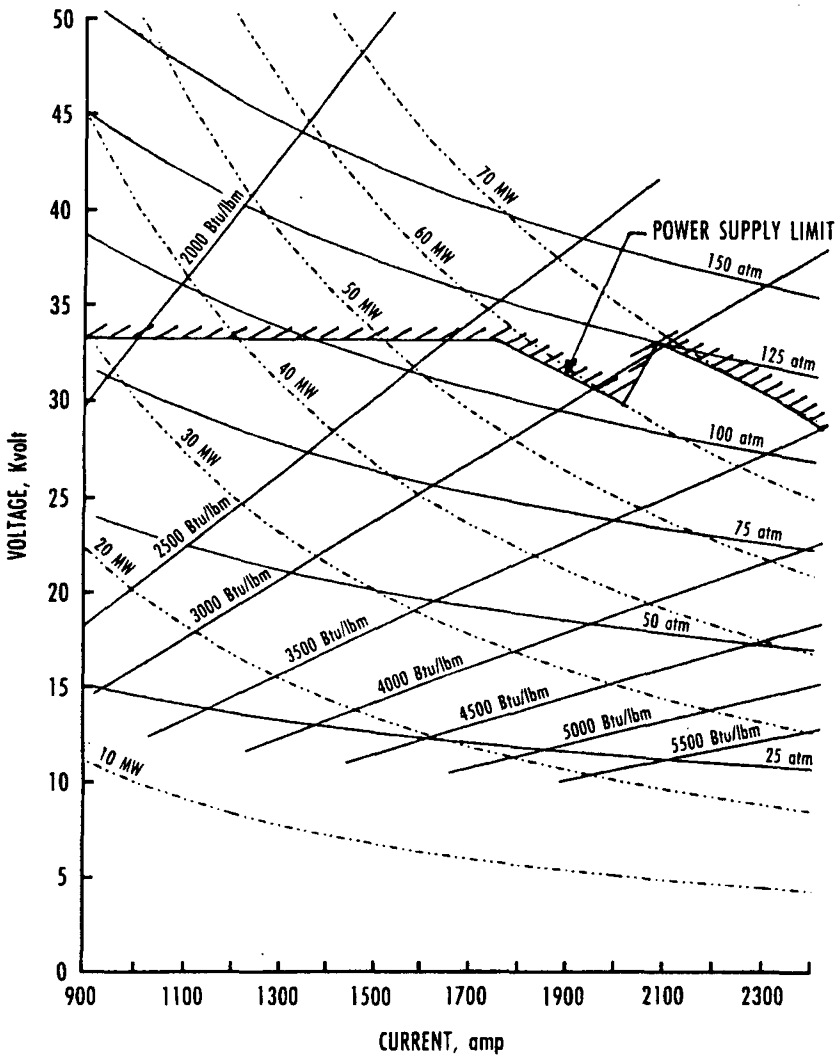


Figure 9. H3 voltage-current envelope with 1.35-in.-diam throat.

constant enthalpy, chamber pressure, and power is shown in Fig. 9. Similar envelopes for the large 1.65-in-diam nozzle throat are shown in Figs. 10 and 11.

The H3 heater has the same pitot pressure altitude - inferred enthalpy envelope as the H1 arc heater, as shown in Fig. 4; however, the H3 heater will provide a 50-percent larger diameter flow field at 2.25 times the mass flow rate and power, which will allow the testing of larger models. The issue of arc heater flow-field contamination from electrode erosion has been a concern to the hypersonic testing community, particularly for propulsion testing. AEDC has addressed the problem and found that the level of contamination from the AEDC H1 segmented heater has a negligible effect on most types of hypersonic testing.[9] The H3 arc heater is expected to have the same low contamination concentrations as H1.

Upon completion of development, the H3 heater is initially planned to be installed in the H2 facility to replace the existing Huels-type heater to improve the facility performance. The H3 heater will improve the pressure, enthalpy, power, and air mass flow rate in the H2 facility. The projected

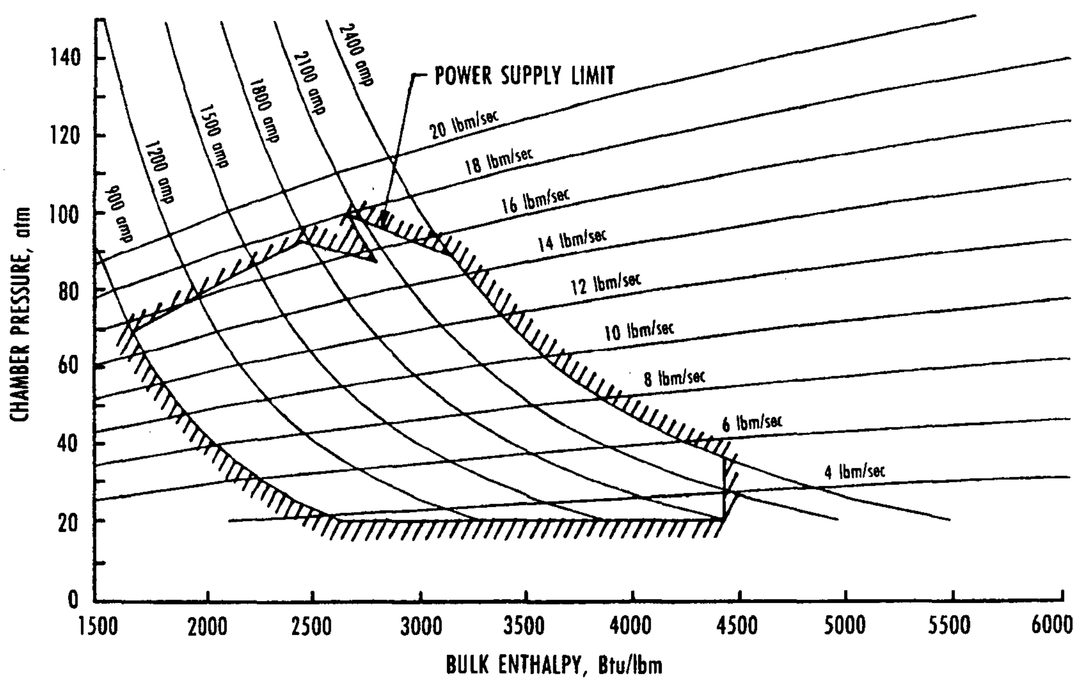


Figure 10. H3 pressure - enthalpy envelope with 1.65-in.-diam throat.

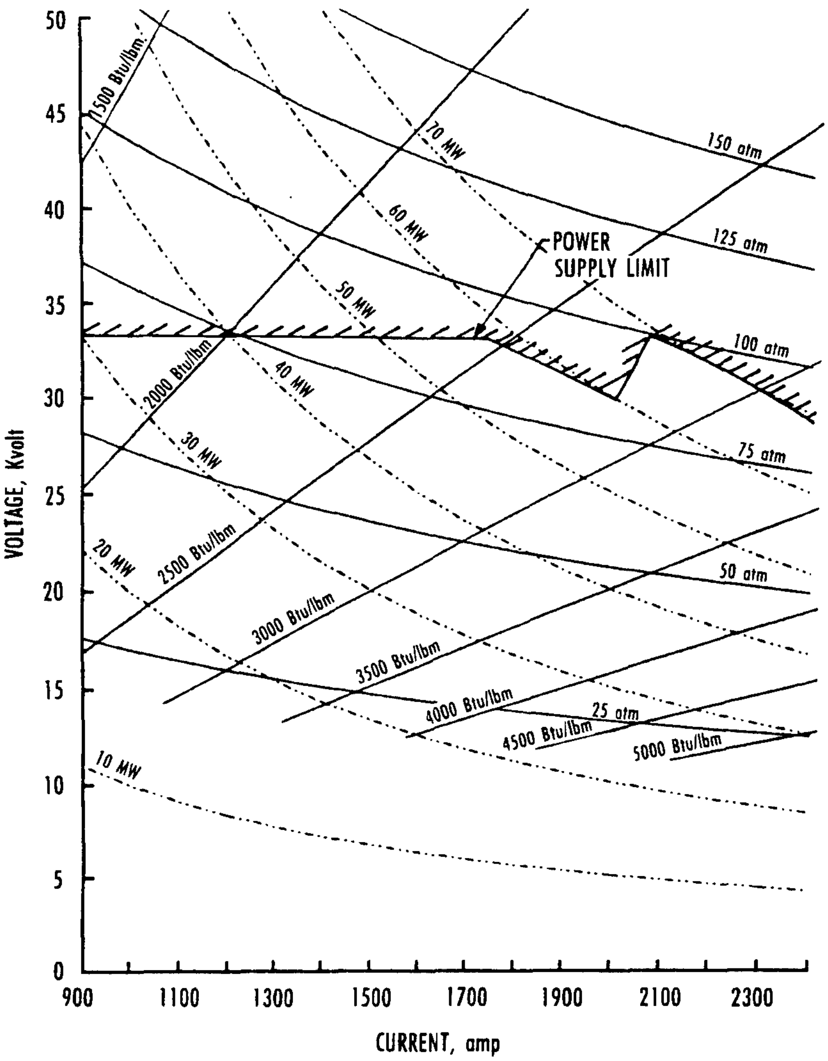


Figure 11. H3 voltage-current envelope for 1.65-in.-diam throat.

improvement in the enthalpy-pressure envelope for the H2 facility with the H3 heater and a 1.5-in.-diam nozzle throat is shown in Fig. 12. The improvement of the aerothermal simulation envelope for stagnation pressure and heat-transfer rate for the H2 facility using the H3 heater is presented in Fig. 13 for 9-in. and 5-in. exit diameter nozzles. Future plans also include upgrading the H1 and/or HR facilities using the H3 heater.

Analytical Efforts

State-of-the-art analytical tools are available at AEDC. In addition, new capabilities are currently being developed, especially in the areas of internal flow modeling and near-electrode modeling.

Historically, the process of scaling arc devices to larger size has relied as much upon empirical scaling relations as upon results of analytical calculations. Scaling relations are generally relatively simple and are easy to use for design studies. Scaling relations have been developed based on experimental operating data and also based on code results. The procedure is illustrated in Ref. 10, in which scaling relations derived from SWIRLARC code results are presented. The SWIRLARC code[11] is a

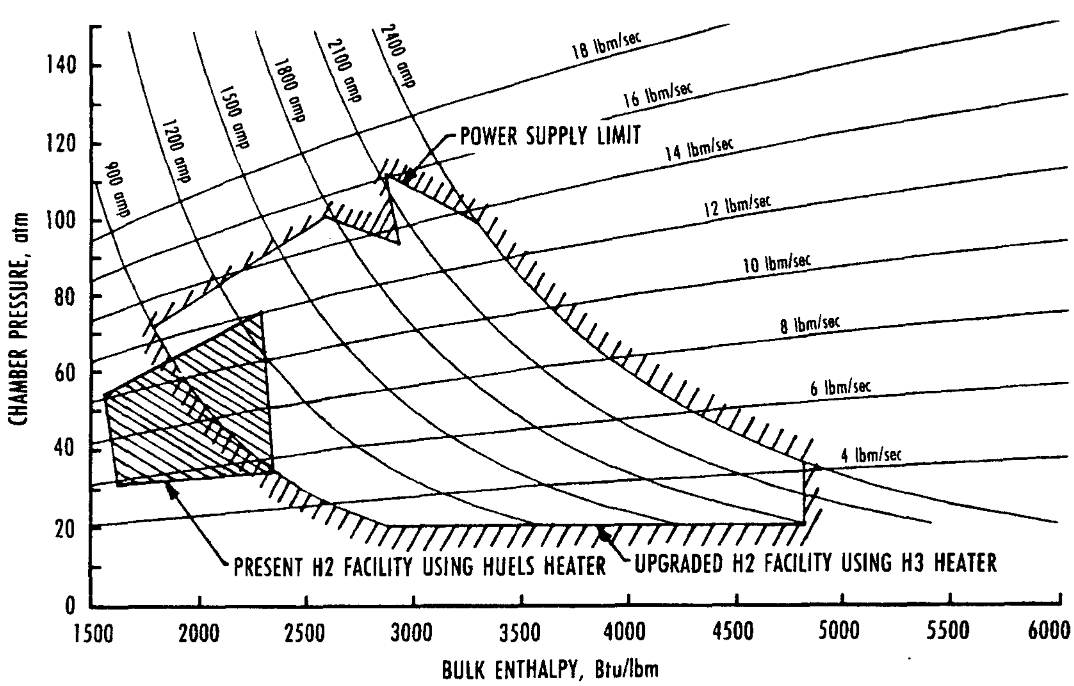


Figure 12. Projected H2 facility pressure-enthalpy improvement using the H3 heater (1.5-in.-diam throat).

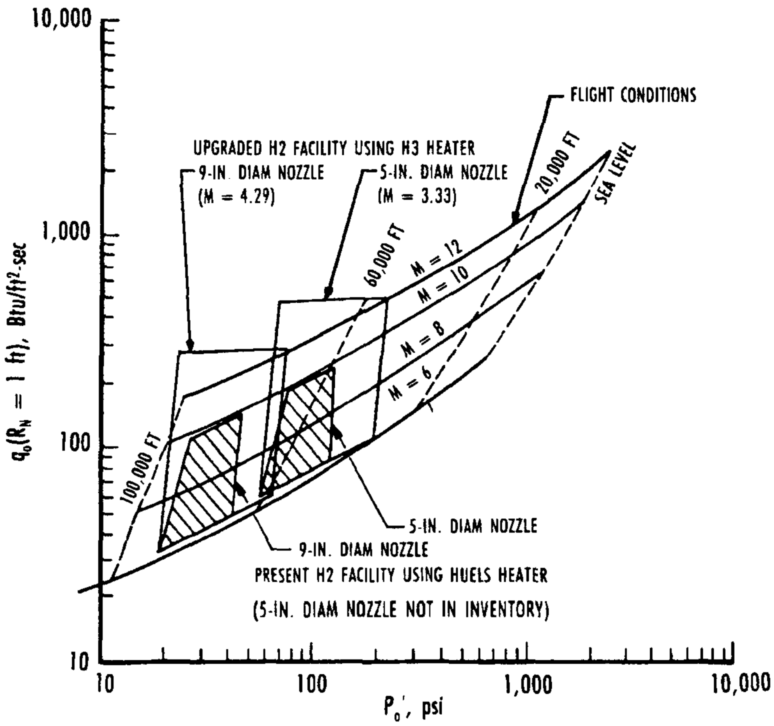


Figure 13. Projected H2 facility aerothermal simulation of flight stagnation pressure and heat-transfer rate using the H3 heater.

state-of-the-art code for computing overall arc heater performance. Recent improvements which have been made to the SWIRLARC code are also reported in Ref. 10.

A computer code, XLIM3D, is currently under development at AEDC to support the arc facilities. XLIM3D is a flexible CFD-type program built upon a 3-D thin-layer Navier-Stokes code written by Reddy and Benek.[12] The code has been extended to incorporate the electromagnetic and radiation transport equations along with the fluid dynamic equations. The radiation model is a multidimensional diffusion model.[13] The equations are solved using a locally implicit algorithm originated by Reddy and Jacocks[14] for solving 3-D compressible Navier-Stokes equations in complex flow domains. The method is based on a point-relaxation scheme applied to the nonlinear equations which result from discretization of the partial differential equations. It does not require linearization of the equations and is completely matrix-free, thus avoiding the computationally expensive evaluation of Jacobian matrices. The algorithm has the unconditional stability associated with implicit schemes, while retaining the simplicity of the explicit schemes. It can easily accommodate auxiliary equations, and source terms do not affect the solution accuracy. Also, it is amenable to vector and parallel processing, unstructured grids, and/or domain decomposition techniques. The three sections (fluid dynamics, electromagnetics, and radiation transport) of the code have been validated individually. However, solutions for combined-field calculations involving the electromagnetics have yet to be attained.

An understanding of the detailed physics of the arc discharge in the immediate region around the attachment to the electrode surfaces, where there is a rapid transition from gaseous to solid-state conduction of electrical current, is key to understanding such issues as electrode survivability and electrode erosion. A comprehensive model for the near-electrode region at high pressure, extending from the flow region all the way into a copper electrode, has been presented in Ref. 15. The approach differs significantly from those previously reported. The concept of a space-charge sheath (which is a zero- or low-current model) is replaced with a thicker, continuum region which is referred to as a current concentration zone. It has long been observed that under certain conditions electrical current "concentrates" in the near-electrode region; the current density in the outer flow is much lower than at the "spot" where it enters the electrode. This phenomenon occurs in arc heaters, MHD devices, rail guns, etc. In the approach adopted here, this experimentally observed variation in current density is imposed on the joule heating term in the heavy gas energy equation. This results in a drastically increasing heat flux as the wall is approached. The present study analyzes the near-electrode region for air at higher pressures (100 atm) than considered in previous studies. At this high pressure, equilibrium ionization at the heavy gas temperature is assumed. A one-dimensional gas-phase analysis is linked to the three-dimensional solid (or liquid) heat conduction zone beneath the electrode surface for a rapidly moving arc spot. This model is consistent with experimental observations of cathode behavior. This model may also prove useful in analysis of current leakage between constrictor segments of high-pressure arc heaters.

More detail on the overall AEDC analytical effort, as well as an assessment of future analytical modeling requirements, is presented in Ref. 16.

High-Pressure Development

The H1 arc heater will be used as the starting point for high-pressure arc heater development. The initial goal is to develop the H1 heater to an operational pressure of 250-atm. Experience gained with the 250 atm development effort will be used to assist in the development to even higher operating pressure (~400 atm). The knowledge gained from the H1 high-pressure development effort will be applied to the H3 arc heater.

The 250-atm operating pressure goal is not a reflection of flight duplication requirements (which are much higher), but rather represents a realistic appraisal of the difficulty in design of an elongated pressure vessel, electrically insulated from end to end, and subject to a 5,000 Btu/ft^2-sec heating rate on the inside wall. The segmented heater design solution is effectively a pressure vessel with over 400 major penetrations, with electrical insulators and O-ring seals at these locations, and with embedded high-pressure cooling water channels. Although protected from the highest heating environment, the seals and insulators must still perform the design function at close to limiting temperatures for non-metallic materials.

It is the combination of arc heater chamber pressure and electrical power which most affects the integrity of the arc heater as a pressure vessel, since those two parameters combined are the primary drivers for wall heating, arc instability, throat survivability, and overall reliability of the heater. The H1 segmented arc heater was designed as a pressure vessel for 200 atm, although the operating design point was 150 atm. As early as 1979, the heater was operated at a pressure of 160 atm and 22.5 MW power with no indication of damage from pressure. In 1987-88, three runs at 150 atm and 30 MW were completely successful. Pressure containment has been successful in the development of H1 to 150 atm, and is not expected to be a major development issue in the 50-percent geometric scale-up to H3, The segmented wall construction, required for arc stability, facilitates an excellent mechanical design for pressure containment of the water-cooled wall; however, special attention must be given to the interface seals and insulators to maintain the integrity under high gas pressure.

Manifolding Experiments

Future AEDC plans include the development of a larger arc heater capability than H3 (currently under development), either by developing a new, even larger heater, or manifolding several H3-size heaters into a common plenum, as illustrated in Fig. 14. Such multi-arc configurations can be a convenient route to higher power heaters, but at somewhat reduced performance because of additional wall cooling losses. A multi-arc configuration may also be an effective way to improve the flow uniformity of both enthalpy and pressure. The mixing of effluents of separate arc heaters in a single plenum may dampen flow-field fluctuations because oscillations in the individual arc units will probably be independent. Investigations are presently underway to determine if the multi-arc approach is feasible to obtain a high-power, large flow-field capability.

Although AEDC is presently developing the next generation arc heater, H3, it does not have a multi-arc capability to acquire the needed data to assess the feasibility and effectiveness of manifolding arc heaters. An extensive program would be required to develop the hardware and modify the electrical, water, air, and data systems at AEDC in order to acquire test data from an arc heater manifold experiment.

Aerospatiale,a Company, located near Bordeaux, France, has a multi-arc heater manifold system (Fig. 15) which has been in operation since 1979. The JP-200 system is comprised of four 5-MW Huels-type arc heaters installed radially at 90 deg to each other in a plane normal to the manifold flow axis. The nozzle centerline is orthogonal to the arc heater flows. The Aerospatiale facility is very attractive to use for manifold experiments because the JP-200 is a mature system with a history of reliable operation.

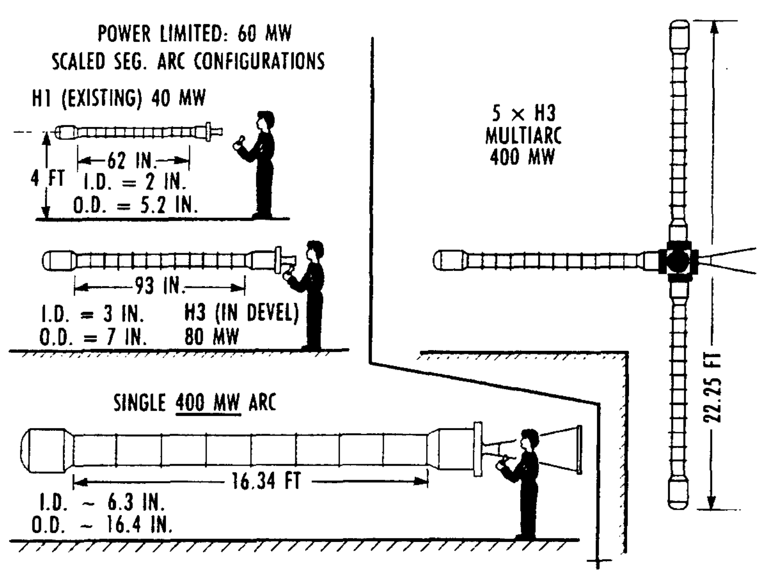


Figure 14. Single-arc versus multi-arc configurations.

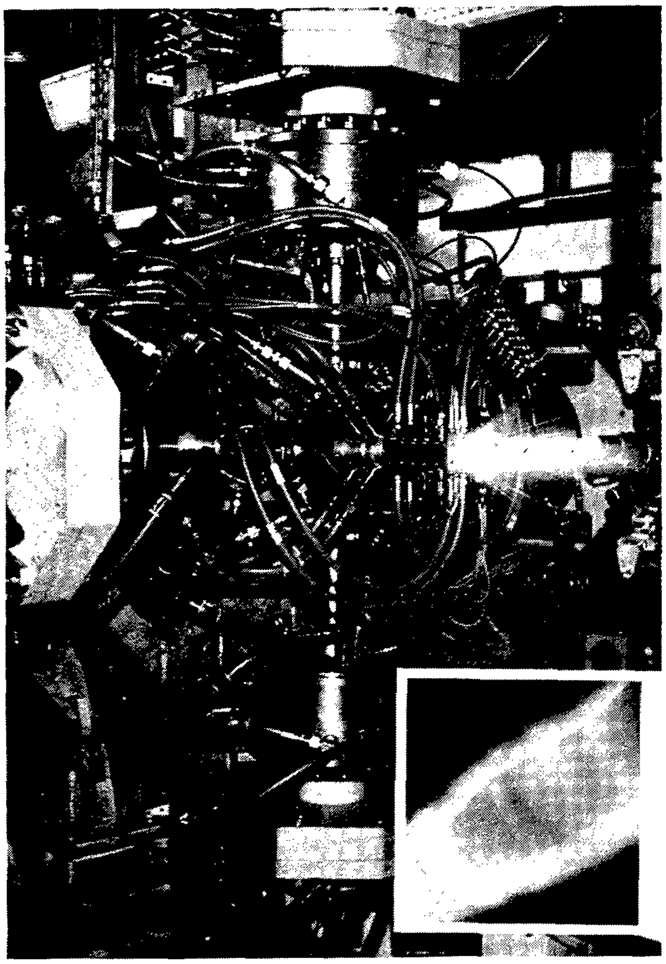


Figure 15. Aerospatiale JP-200 multi-arc facility.

An effort has been funded with Aerospatiale to investigate arc heater manifolding using the JP-200 multi-arc facility and the single-arc HP facility. Flow-field data will first be acquired from a single arc heater (HP) similar to one of the JP-200 arc heaters without a manifold, to establish a baseline for flow-field fluctuations and profile. The JP-200 system will then be operated in various configurations with different numbers of heaters manifolded and energized and with cold air mixing. Flow-field data from the multi-arc facility will be compared with data from the single arc facility to evaluate the improvement in flow-field fluctuations and profile. The overall thermal efficiency of the multi-arc manifold system will also be evaluated.

The manifold evaluation test is scheduled for September 1994.

Additional Development Efforts

Several other activities are being pursued by AEDC in coordination with other facilities relative to arc heater development. Internally water-cooled enthalpy and pitot-pressure probes with the capability to dwell on the flow-field centerline are presently being developed by Sparta, Inc., located in Temecula, California. Prior to this development effort, all arc facility diagnostic probes were swept through the flow field, giving a transient profile of the flow. The new probes are designed to obtain steady-state enthalpy and pressure data in the flow field. The enthalpy probe uses a double sonic orifice technique to determine the flow-field enthalpy. Both probes use the proprietary Sparta diffusion-bonded foil construction to form the internal cooling water passages. The internally cooled probe development effort is presented in Ref. 17.

The AEDC has recently funded two small contracts to investigate the possibility of coating arc heater segments with a high thermal conductivity, high electrical resistance material. If segments can be coated with such a material that would withstand the severe arc heater environment, the arc stability in the heater would be improved by reducing the possibility of damage to the segments from arc breakdown and conduction along the constrictor wall.

Air is injected into the arc heater tangentially to create a vortex to help stabilize the arc on the bore centerline. A vortex breakdown in the arc heater can have catastrophic results when the arc strikes the heater wall and causes serious damage. Vortex stability and breakdown are being studied by the University of Tennessee Space Institute (UTSI) located near Tullahoma, Tennessee. Some of the early results of the vortex study are presented in Ref. 18. UTSI has recently used a twice-scale H1 water tunnel model to study the factors which promote or degrade the vortex stability.[19]

Summary

AEDC has undertaken an aggressive arc heater development program to develop larger, more capable arc heaters to satisfy some of the future hypersonic testing requirements. A new large arc heater (H3) is presently under development and is scheduled to be fully operational at chamber pressures up to 115 atm by late 1995. Future plans also include the development of still higher pressure arc heaters and the development of a larger, higher power capability by manifolding several arc heaters into a single plenum or by developing a single very large arc heater. AEDC has also developed an extensive analytical capability to assist in the design and development of arc heaters. This effort has also broadened the base of knowledge in arc physics and arc heater reliability.

References

1. Horn, D. D. and Smith, R. T. "AEDC High-Enthalpy Ablation Test (HEAT) Facility Description, Development, and Calibration." AEDC-TR-81-10 (AD-A101747), July 1981.

2. Bruce, W. E.,III and Horn, D. D. "AEDC Arc Column Diagnostic Measurements." Proceedings of the 38th International Instrumentation Symposium, Paper No. 92-0190, April 1992.

3. Felderman, E. J., Horn, D. D., Carver, D. B., and Davis, L. M. "AEDC Expanded Flow Arc Facility (HEAT-H2) Description and Calibration." Proceedings of the 38th International Instrumentation Symposium, Paper No. 92-0191, April 1992.

4. Smith, D. M. et al. "An Experimental Technique for Measuring RF Performance of Hot Antenna Windows in the AEDC HEAT-H1 Arc Heated Test Unit." Twentieth Symposium on Electromagnetic Windows at Georgia Institute of Technology, Atlanta, GA, September 1992.

5. Amundson, M. H. and Smith, D. M. "Ground Test and Evaluation Methodologies and Techniques for the Development of Endoatmospheric Interceptors." AIAA Paper No. 93-2679, June 1993.

6. Stewart, J. H. "AEDC -H2 Facility - New Test Capabilities for Hypersonic Air Breathing Vehicles." AIAA Paper No. 93-2781, 1993.

7. Sherrouse, P. and Carver, D. "Demonstrated Real-Time Recession Measurements of Flat Materials During Testing in High-Enthalpy Flows." AIAA Paper No. 92-0765, January 1992.

8. Horn, D. D., Felderman, E. J., and MacDermott, W. N. "Analysis and Results of External Magnetic Fields Applied to High Pressure DC Electric Arc Heaters." AIAA Paper No. 94-2040, June 1994.

9. MacDermott, W. N. Horn, D. D. and Fisher C. J. "Flow Contamination and Flow Quality in Arc Heaters Used for Hypersonic Testing." AIAA Paper No. 92-0408, July 1992.

10. MacDermott, W. N. and Felderman, E. J. "Arc Heater Scaling Parameters Predicted with the SWIRLARC Code." AIAA Paper No. 93-2797, 1993.

11. Shaeffer, S. F. "SWIRLARC: A Model for Swirling, Turbulent, Radiative Arc Heater Flow Fields," AIAA Paper No. 78-68, 1978.

12. Reddy, K. C. and Benek, J. A. "A Locally Implicit Scheme for 3-D Compressible Viscous Flows." AIAA Paper No. 90-1525, June 1990.

13. Felderman, E. J. and MacDermott, W. N. "Radiative Heating in High-Pressure Arc Heaters." AIAA Paper No. 92-2873. 1992.

14.) Reddy, K. C. and Jacocks, J. L. "A Locally Implicit Scheme for the Euler Equations." AIAA Paper No. 87-1144-CP, June 1987.

15. Felderman, E. J., MacDermott, W. N. and Fisher, C. J. "Near-Electrode Model at High Pressure (100 atm)." AIAA Paper No. 94-2039, 1994.

16. Felderman, E. J., Chapman, R. and Jacocks, J. L. "Development of a High Pressure, High Power Arc Heater: Modeling Requirements and Status." AIAA Paper No. 94-2658, June 1994.

17. Graves, C. M., Moody, H. L., Mitchell, J. D. and Horn, D. D. "Enthalpy Probe for Arc Heater Flow Diagnostics." AIAA Paper No. 93-2784, July 1993.

18. Vakili, A. D., et al. "Increasing and Decreasing the Stability of a Confined Vortex by Forcing." AIAA Paper No. 93-3039, 1993.

19. Tennent, S. G. "Experimental Investigation of a Confined Vortex Flow." Master of Science Thesis, University of Tennessee, Knoxville, December 1993.